Fusion: power and the future?

Background Paper

BP-291E

FUSION: POWER FOR THE FUTURE?

Alan Nixon
Science and Technology Division

April 1992

Library of Parliament
Bibliothèque du Parlement

Research Branch

The Research Branch of the Library of Parliament works exclusively for Parliament, conducting research and providing information for Committees and Members of the Senate and the House of Commons. This service is extended without partisan bias in such forms as Reports, Background Papers and Issue Reviews. Research Officers in the Branch are also available for personal consultation in their respective fields of expertise.

Available in Canada through
your local bookseller
or by mail from
Canada Communication Group -- Publishing
Ottawa, Canada K1A OS9

Catalogue No. YM32-2/291E
ISBN 0-660-14582-0

CE DOCUMENT EST AUSSI
PUBLIÉ EN FRANÇAIS

CANADA

LIBRARY OF PARLIAMENT
BIBLIOTHÈQUE DU PARLEMENT

FUSION: POWER FOR THE FUTURE?

INTRODUCTION

Fusion power is the holy grail of the scientific world. Scientists have already been on the quest for about four decades and the end is not yet in sight. Fusion, which was first explained by Hans Bethe in the late 1930s, is the process which lights the sun and stars. Controlled fusion is enormously difficult to achieve on earth, however, and, although a great deal of progress has been made, it is believed it will take at least another three decades before fusion power can become an economically viable proposition.

Two recent events have brought fusion back before the public eye. One was the announcement of "cold fusion," the claim that fusion had been achieved, albeit in a very limited way, in a simple electrolytic cell. Had the claim been true, and it now appears certain that it was not, it would have revolutionized fusion science. The other event was the announcement in November 1991 that the Joint European Torus (JET) had produced a two-megawatt pulse of power lasting almost two seconds. This was the first time a significant amount of power had been produced in a fusion reactor.

Why is fusion power so attractive that research programs have been supported for so long, even though the reward, if it comes at all, is still far in the future? Compared to conventional nuclear power, fusion is very safe; fusion is also environmentally benign, since it emits no acid rain-forming or greenhouse gases. The fuel is relatively cheap and virtually unlimited.

The fuel is a form of hydrogen, which is the major component of the universe and is present on earth in vast quantities in the oceans as water. The combination of high temperature and pressure, under which fusion occurs in stars, cannot be duplicated on earth and finding a practical way of tapping, in a controlled fashion, the energy in the hydrogen atom is a formidable challenge.

BASIC PRINCIPLES

Nuclear energy, both fusion and fission, depends on the energy that binds atomic nuclei together. The mass of the atomic nucleus is slightly less than the total mass of the separate protons and neutrons that form it. This phenomenon is known as the "mass defect." The relationship between mass and energy is given by Einstein's famous equation: $E=mc^2$ where E is energy, m is mass and c stands for the speed of light. Because the speed of light is so great, 300 million metres per second, even a small amount of mass is equivalent to an enormous quantity of energy. One gram of matter converted completely to energy would produce 90 million million joules, equivalent to the energy produced by burning 15,000 barrels of oil. The mass defect reaches its maximum value at iron, which is about midway in the periodic table of elements. In principle, atomic nuclei lighter than iron can release energy by combining or fusing to form heavier nuclei, while nuclei heavier than iron can release energy by splitting apart in the process known as fission. Fission is the process that provides the source of energy in conventional nuclear power and in the atomic bomb.

Although, theoretically, all the elements lighter than iron can fuse to release energy, only a few of the lightest elements, hydrogen, helium, and lithium, could be made to do so under conditions that could conceivably be produced on earth. For fusion to occur, very high energies are needed to overcome the electrical repulsion between the positively charged nuclei. Even for the lightest atoms, fusion requires temperatures of tens to hundreds of millions of degrees celsius. Table 1 shows some examples of fusion reactions and ignition temperatures. The symbols

D and T stand for deuterium and tritium, forms of hydrogen that differ from ordinary hydrogen (H) by having one and two neutrons respectively in the nucleus in addition to the proton. The proton-proton reaction, which is the basic energy-producing process in the sun and most stars, requires the high temperatures and pressures found in the core of the sun.

Table 1

Examples of Fusion Reactions

Reaction	Energy Per Gram of Reactants (joules)	Ignition Temperature (millions °C)
$D + T \rightarrow {}^4He + n$	34×10^{10}	45
$D + D \rightarrow T + p$	10×10^{10}	650
$D + D \rightarrow {}^3He + n$	8×10^{10}	900
$D + {}^3He \rightarrow {}^4He + p$	36×10^{10}	220

For the foreseeable future, only the deuterium-tritium reaction seems attainable and is the fusion goal being pursued worldwide. Only a small part of the deuterium and tritium mass is converted to energy; nevertheless, the amount of energy generated is immense. One gram of mixed fusion fuel is equivalent to almost 100,000 kilowatt-hours of electricity or 60 barrels of oil.

The ignition temperatures in Table 1 are the minimum under which a self-sustaining fusion reaction could be ignited in an ideal system. In reality, because of energy losses, temperatures of 200 to 300 million degrees will probably be required in practical fusion reactors. Although these temperatures may seem almost beyond comprehension, they are already being routinely achieved in fusion experiments.

Temperatures of hundreds of millions of degrees are far beyond the realm of material containers. How, then, can the intensely hot reactants be contained or "confined" long enough and at sufficient density for fusion to occur? There are currently two basic approaches to fusion: magnetic confinement fusion (MCF) and inertial confinement fusion (ICF). Gravitational confinement, which makes possible the sun's nuclear reactions, is not possible on earth.

Magnetic confinement depends on the special properties of a form of matter called a plasma. At a sufficiently high temperature, electrons are separated from the atoms of gas resulting in a state consisting of negatively charged electrons and positively charged ions. This state is called a plasma and is often referred to as the fourth state of matter after solid, liquid and gas. Although plasmas may seem exotic, they are quite commonly encountered in the form of lightning flashes and neon lights. The properties of a plasma differ in some fundamental ways from those of a gas. Unlike the neutral particles of a gas, the charged particles of a plasma interact with a magnetic field and can be trapped by an appropriately shaped magnetic field. Magnetic trapping is fundamental to magnetic confinement fusion machines. Also, unlike a gas, a plasma is a good electrical conductor. This property too is important in the design of fusion machines.

The inertial confinement approach is quite different. It depends on the rapid implosion and heating of a tiny pellet of fuel, only few millimetres in diameter, using laser or particle beams. The energy focused by the beams on the surface of the pellet causes intense heating and blasts the surface away almost instantaneously. This creates a shockwave which compresses the pellet into a high-density, high-temperature plasma, where fusion occurs almost instantaneously, almost like a miniature hydrogen bomb.

One of the biggest challenges of ICF is to make efficient use of the beam energy to implode the pellet. In the case of laser beams, this depends on a number of factors including the wavelength of the laser light and the intensity of the laser beam. Another major challenge is to develop lasers or particle beam generators with sufficient power and efficiency to make ICF practical. Work on the ICF approach was begun in the U.S. in the early 1970s and significant advances were made in the 1980s but, at present, MCF is more advanced.

Although a limited amount of work is being done in Canada on ICF, the Canadian fusion program is concentrated on magnetic confinement; the rest of this review will focus on this approach.

TECHNOLOGY

A. Confinement

A number of magnetic field configurations can be used to trap the plasma, of which the most successful by far to date is the "tokamak," which confines the plasma in a ring, or "torus" by means of a suitably shaped magnetic field. The concept was conceived in the U.S.S.R. in the 1950s and the name tokamak is derived from the Russian words for toroidal magnetic chamber. The field must keep the plasma away from the walls of the chamber, not only, as mentioned earlier, because the temperature would destroy the walls, but also because the plasma would lose too much heat to sustain the high temperatures required. A more subtle reason is that impurities from the chamber wall would degrade the plasma.

B. Heating

The plasma can be heated in several ways. Inductive heating, in which the plasma loop acts as the secondary circuit of a transformer, can be used to reach temperatures of 10 to 50 million degrees. Higher temperatures of up to 300 million degrees can be achieved by auxiliary heating with radio-frequency energy or the injection of very high speed beams of electrically neutral hydrogen or deuterium.

Overall performance can be measured in terms of a factor Q, which is the ratio between the fusion energy produced and the external energy used to confine and heat the plasma. When the input and output energy are equal, Q has a value of 1. This state, referred to as "breakeven," is the benchmark for a feasible fusion reaction. To obtain ignition, in which the temperature of the plasma is sustained by heat from the fusion reaction itself rather than by external heating, requires a Q value of around 5 to 10.

Eighty percent of the energy of the fusion reaction is in the form of energetic neutrons which, being electrically neutral, escape from the magnetic field of the reactor. In a working reactor, they would be captured by a lithium blanket, where they would give up their energy to a heat exchanger. This heat would then be used to generate electricity by conventional technology such as a steam turbine.

C. Fuel

The first generation of fusion reactors will burn a fuel mixture of deuterium and tritium. Deuterium is a non-radioactive, naturally occurring isotope of hydrogen which has an abundance of 0.015% of natural hydrogen. As one cubic metre of water contains 33 grams of deuterium and the earth's oceans contain 1.5 billion cubic kilometres of water, the supply of deuterium is virtually inexhaustible. Canada is already a world leader in deuterium extraction technology since deuterium, in the form of heavy water, is an essential component of the Candu nuclear power system.

Tritium does not occur naturally, however. It is radioactive and has a half-life of only 12 years. After an initial start-up charge of tritium, a reactor would have to generate its own. Fortunately, the neutrons captured in the lithium blanket react with the lithium nuclei to produce or "breed" tritium by the reactions:

$$6Li + n \rightarrow {}^4He + T$$

$$7Li + n \rightarrow {}^4He + T + n$$

Known world lithium deposits are 10 million tonnes, enough to support a deuterium-tritium fuel cycle for several hundred years at a conservative estimate.

Canada also has advanced tritium-handling technology. In fact, the Tritium Removal Facility at Ontario Hydro's Darlington Nuclear Generating Station is the world's largest civilian source of tritium.

Canadian consumption of electrical power in 1988 was 482 terrawatt-hours. This amount of power could be supplied by a total of only 2 tonnes of deuterium and 3 tonnes of tritium bred from 33 tonnes of lithium. About 60 million tonnes of coal or almost 300 million barrels of oil would be required to produce the same amount of electricity.

D. Safety and Environmental Impact

Fusion reactors potentially offer two major safety advantages over conventional nuclear power plants. Perhaps the most important of these is that fusion reactors present no possibility of a

meltdown or a catastrophic explosion like that at Chernobyl; there is simply not enough fuel or stored energy in the reactor at any one time to cause such an accident. The other advantage is that, because the reaction is so difficult to initiate and maintain, it is essentially failsafe. Any system failure, such as a leak in the reaction chamber or a disruption of the magnet power supply, would immediately shut down the fusion reaction.

Unlike conventional nuclear power, which generates radioactive waste in the form of long-lived fission products, the by-product of fusion is helium, which is completely inert. Fusion power is not without some inherent risks, however. There will be some atmospheric release of radiation from an operating plant, mainly in the form of tritium from fuel-handling operations. Even here, there is a significant advantage over conventional nuclear power, however, since tritium is relatively short-lived with a half-life of 12.3 years. It is estimated that fusion plants will emit about 1% or less of the radioactive emissions from a comparable fission plant. Incidentally, coal-fired power plants emit amounts of radiation comparable to those from conventional nuclear plants of similar capacity. The main radiative waste from a fusion plant will be the plant itself, which will become radioactive through neutron activation of the components. To some extent, this can be minimized through judicious choice of materials, but it is possible that the volume of radioactive waste from a fusion plant will exceed that from a conventional nuclear power plant. An important distinction, though, is that these wastes, unlike fission wastes, will be relatively short-lived.

The environmental impacts of fusion power should be small. Like conventional nuclear power plants, fusion power plants will emit neither greenhouse nor acid rain-forming gases. The fuels, deuterium and lithium, are not radioactive and are otherwise quite safe and, in view of the small quantities required, pose minimal risk of transportation accidents, whose effects in any case would be nothing in comparison to the effects of a spill from an oil tanker.

THE INTERNATIONAL FUSION PROGRAM

A. International Cooperation

About 30 countries are currently involved in fusion research, mainly on the magnetic confinement approach. Because of the high cost of such research, about $2 billion per year, there is extensive international cooperation, including the sharing of information, building and operating fusion machines, and conducting experiments. Worldwide, around 10,000 scientists, engineers, technical staff and others are involved in fusion programs.

The largest fusion programs are supported by Europe, the U.S., Russia and Japan. Each has a major "flagship" tokamak reactor costing about $1 billion. It was at one of these reactors, JET (the Joint European Torus) located at Culham in the U.K., where the widely reported "breakthrough" experiment of last fall was conducted. A major purpose of the "big" tokamaks is to achieve breakeven (Q=1). There are about 30 other medium-sized, advanced tokamaks doing specialized work around the world, including the Canadian Tokamak de Varennes.

B. The International Thermonuclear Experimental Reactor, ITER

The next major step in fusion research will be the International Thermonuclear Experimental Reactor (ITER), which is intended to demonstrate the feasibility of magnetic confinement fusion power. ITER, unlike previous tokamaks, will be designed to achieve ignition.

The technological and engineering demands on ITER will be extreme. It will burn a mixed fuel of deuterium and tritium and operate at a temperature of 200 million degrees. The magnetic fields that confine the plasma will be generated by superconducting coils. The intense heat and radiation will require the development of new high-temperature, erosion-resistant materials to line the chamber. Damaged internal parts, made radioactive by irradiation with neutrons, will have to be replaced regularly by advanced remote handling technology.

ITER will be a major undertaking. The cost of construction is estimated to be about $5.8 billion and another $1.5 billion will be

incurred in design and research and development costs. The costs will be borne by the partners, Europe, the U.S., Japan and Russia, which has assumed the place of the former Soviet Union in the project. The partners will also pool their knowledge and share in the benefits. The cost, though large, is not out of line with that of conventional nuclear power. By way of comparison, the cost of one 935 MW unit at Darlington is about $3.4 billion.

The basic design for ITER was conceived during 1988-1990 at the Conceptual Design Activities (CDA), which had its headquarters at the Max Planck Institute in Germany.

An agreement to proceed with the engineering design phase of ITER was reached in July 1991. Design centres will be located in San Diego, California; Garching, Germany; and Naka, Japan; with an ITER council in Moscow, Russia to provide general oversight. Engineering Design Activities (EDA) started in 1991 and will continue to be refined through 1996.

The final decision to build ITER will probably not be made before 1997, although the site should have been selected a year earlier. It may be difficult, for various reasons, to reach an agreement to locate ITER in the territory of one of the four principal collaborators and there is a slight possibility that another country could be chosen to be the host. In some ways, Canada might be an reasonable compromise. It could certainly provide the infrastructure and the technical support and would have little difficulty in playing host to an international community of fusion researchers. There might, however, be an expectation for the host country to make a substantial contribution to the construction costs in order to offset the benefits to the local economy. Such an obligation would be difficult for Canada to meet.

Construction of ITER should begin in 1997 and be completed in 2004. ITER will be commissioned in 2005 and should by then be producing fusion energy. Although it will produce 1,000 megawatts of fusion power, it will not produce electrical power. A prototype fusion power plant would be the next major step.

Participation in ITER is not limited to the "big four." Canada has been participating in ITER since 1988 through the European fusion program.

THE CANADIAN FUSION PROGRAM

By international standards, the Canadian fusion program is relatively small. At $25 million a year, it represents a little over 1% of the total world effort. The major contributors to the Canadian program are the federal government, the governments of Quebec and Ontario and Ontario Hydro and Hydro-Québec. Federal funding to the fusion program is allocated by the Panel on Energy Research and Development. The National Fusion Program (NFP), operated by AECL research, has responsibility for coordinating fusion work in Canada and manages the federal funding.

The Canadian fusion effort is concentrated in two principal programs: *le Centre canadien de fusion magnetique* (CCFM), near Montreal, and the Canadian Fusion Fuels Technology Project, near Toronto.

A. *Le centre canadien de fusion magnetique*, CCFM

CCFM, which is supported by NFP, Hydro-Québec and INRS-Energie, operates the Tokamak de Varennes, Canada's most advanced tokamak facility. The centre specializes in magnetic confinement technology and reactor materials science and employs a total staff of 90, 50 of whom are scientists and 25 technicians.

The Tokamak de Varennes was not intended to achieve fusion but to study two important aspects of fusion reactor development: plasma-wall interactions and long-pulse operation. Erosion of wall materials tends to degrade plasma performance by incorporating atoms from the wall material into the plasma. CCFM is studying advanced methods of controlling and minimizing these impurities. Conventional tokamaks can typically create second-long plasma pulses. The Tokamak de Varennes is designed to produce 30-second magnetic confinement fields. It is able to do this, in part, because of the abundant power available from the Hydro-Québec grid. In order to take advantage of the long confinement, CCFM is developing a

radio-frequency method of injecting power into the plasma. This will allow the Tokamak de Varennes to generate conditions closer to the steady state needed for practical fusion reactors. To put this in perspective, the duration of the two-megawatt pulse in the JET experiment was only two seconds.

B. The Canadian Fusion Fuels Technology Project, CFFTP

CFFTP is an R&D management centre which contracts out R&D work in Canada and exports expertise and engineered fusion systems to other countries. It is funded jointly by NFP, the Province of Ontario through the Premier's Technology Fund, and Ontario Hydro. It also generates revenues from the sale of technology and hardware.

CFFTP's principal research and development activities include:

- tritium handling technology;
- breeder blanket technology;
- remote (robotic) handling equipment;
- fusion reactor design, including input to ITER; and
- safety and environmental studies.

In addition, CFFTP collaborates with other fusion programs, notably ITER, the International Thermonuclear Experimental Reactor; JET, the Joint European Torus; and TFTR, the Tokamak Fusion Test Reactor in the U.S. CFFTP has already participated in the Conceptual Design Activities for ITER and will take part in the Engineering Design Activities. Another important function of CFFTP is the transfer of fusion knowledge from research and development centres to industry in order to broaden the strength of the industrial base in fusion technology.

C. University and Industry

Fusion-related research is also being carried out in universities. Eleven Canadian universities have programs in areas including magnetic and inertial confinement, advanced materials, and the

effects of tritium on materials. The university work is supported in part by the Natural Sciences and Engineering Research Council and in part by CCFM and CFFTP.

Canadian industry is also very much a part of the fusion program. The Tokamak de Varennes, which cost nearly $50 million to build, was designed by Canadian scientists and built by Hydro-Québec and other Canadian companies. In fact, 85% of the cost of the project was spent in Canada. For example, Canatom Inc. designed the reactor proper, while the fibre-optic control system was designed by MPB Technologies. Canatom is now bidding on reactor design projects in the U.S. and MPB is selling similar control systems to fusion laboratories in the U.S. and Europe. SPAR Aerospace, the company that built the Canadarm for the space shuttle, is now using similar technology to develop remote handling systems for fusion reactor maintenance.

THE FUTURE OF FUSION

Despite the success of the JET experiment and the universal acclamation of the fusion community, a future of inexpensive, widely available fusion energy is not assured. Even though the fuel would be relatively cheap and virtually inexhaustible, and fusion power should be environmentally benign and safe, there is little doubt that the technology would be very expensive. Thus, it is possible, even if all the scientific and engineering problems can be solved, that the complexity of the system and the material requirements might preclude fusion as an economically viable power source.

The costs of fusion research have escalated considerably during recent years to the point where no individual nation, not even the economic super powers, can afford an independent program. This has its benefits, however, in that it has brought about an almost unprecedented scale of international cooperation in "big science." Continued support for fusion research is not guaranteed. The U.S. Energy Department has cancelled plans for the Burning Plasma Experiment at Princeton, which would have cost $1.4 billion; JET is facing layoffs because of cuts to its annual

budget of \$149 million; and the EC has yet to approve funding beyond 1993. The Canadian program, too, has been threatened by a proposed reduction of CCFM's annual budget from \$14 million to \$10 million. An announcement was made at the end of March 1992, however, that the budget for CCFM in 1992 would be \$14.4 million.

Some sceptical observers have suggested that JET experiment was more of a publicity exercise timed to boost flagging political support than a real scientific breakthrough. To some extent, this may be true. Another reason for the timing of the experiment might have been the desire, always present in science, to be first, in this case to beat TFTR to the mark. Nevertheless, the JET experiment does appear to have been a genuine achievement. The energy produced exceeded by more than 100-fold the energy produced in previous controlled fusion experiments. More importantly perhaps, the results confirmed the predicted performance. The value of Q for the November JET experiment was 0.15 but this was achieved with only 10% tritium in the fuel mixture. Had JET used a 50/50 mixture of deuterium and tritium, Q would have been 0.46 and had the test been done with JET's best plasma, it has been estimated that Q would have been 1.14. In other words, JET appears capable of achieving breakeven.

Actual breakeven may be achieved in 1993, however, when TFTR begins deuterium-tritium experiments in which researchers hope to generate 30 megawatts of fusion power. Ignition, however, will probably not be achieved until ITER comes on stream.

Despite the progress signified by the JET experiment, there is still a very long way to go before fusion can become a practical reality. For example, there are still unanswered questions about the fundamental nature of the plasma. These questions will be answered in the first of the two operational phases of ITER, expected to last six to eight years, during which workers will attempt to achieve ignited burning plasma conditions similar to those in a working fusion reactor. The second stage will be a multi-year program focusing on the technology and engineering, including the integrated performance and alternative materials and designs. Given the number of tests needed and the time required to carry them out, it is not surprising that even a prototype fusion power reactor is still many years in the future.

The lessons learned from fusion research will not be limited to fusion technology and there will undoubtedly be spin-off benefits. Many aspects of high technology find applications in different fields. For example, the layer of heat resistant tiles that protect the inner surface of the torus from the plasma are similar to the tiles that protect the undersurface of the space shuttle.

If Canada is to compete in the international marketplace, it must invest in advanced science and technology. The goal of practical fusion power may still be distant, but participation in the program assures Canadian scientists and engineers of a place at the forefront of one of the most important "big science" projects of our time. Just as importantly, it will provide an opportunity for Canadian industry to compete in leading edge technologies. Can Canada afford to have a nuclear fusion program? Perhaps the question should be, can it afford not to?